Technical Paper

DARPA Grand Challenge

23 February, 2004

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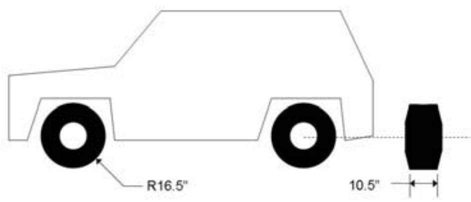
1. System Description

a. Mobility

1. Describe the means of ground contact. Include a diagram showing the size and geometry of any wheels, tracks, legs, and/or other suspension components.



Our vehicle platform, a 2-door 1996 Chevy Tahoe, will contact the ground with 4 pneumatic BFGoodrich Baja T/A KR (Kevlar-belted) tires, size 35/12.50/R15. The width of the contact area is ~10.5", as shown in the diagram at left.

2. Describe the method of Challenge Vehicle locomotion, including steering and braking.

The challenge vehicle is a standard production vehicle (1996 Chevrolet Tahoe K1500 4x4) with the steering column removed and replaced with a servomotor driving the stock rack and pinion power steering system. A linear actuator is connected to the rear of the brake pedal via a cable for autonomous braking, using the stock front disk and rear drum brakes. Throttle control is accomplished using a linear actuator connected to the cruise control cable.

3. Describe the means of actuation of all applicable components.

Our Challenge Vehicle has actuators installed to allow computer control of the vehicle's motion. The engine is a 5.7 liter Chevy Vortec V8, with a manually controlled automatic transmission and transfer case. The transfer case will be used only in high range four wheel drive mode (i.e., there will be no transfer case actuator).

The brakes are controlled by an Ultramotion™ linear actuator, which is connected to the brake linkage by a steel cable attached behind the brake pedal. The actuator is driven by a Quicksilver SilverMax™ motor and control system which is in turn connected to the computation system by a serial port. Since the brake pedal is pulled by a cable, an operator riding in the vehicle can still press the pedal (the cable attached to it simply buckles). A gas spring is installed in parallel with the linear actuator. If power is lost to solenoids keeping the gas spring retracted (e.g., during a disable e-stop), this gas spring extends and applies sufficient force to quickly stop the vehicle.

The vehicle's throttle is controlled by a proportional Addco ERC linear actuator which is controlled by a potentiometer connected to the on-board computers through a parallel port. The actuator connects to the stock cruise control cable allowing a human to manually control acceleration with the gas pedal.

The transmission is controlled by a positional Addco ERC linear actuator which is preset with 4 positions. The control is connected to the computing system by a parallel port.

The steering is controlled by a Parker servomotor connected to the input of the power steering gearbox. The servo is controlled via a serial port on the control computer. The steering wheel is replaced with a joystick that can be used for manual control of the steering.

b. Power

1. What is the source of Challenge Vehicle power?

All electrical power will be supplied by a Honda EV6010 RV generator, capable of delivering 6000W continuously at 120VAC. Two uninterruptible power supplies by Acumentrics (RuggedUPS 2500) will provide backup power to all critical systems for approximately 40 minutes. The rated output of each of these devices is a continuous 2000W at 120VAC. Run in parallel, the system will provide 4000W. DC Power will be provided by a Cosel ACE900 900W power supply providing 300W each of 12VDC, 24VDC, and 48VDC. Driveline power will be supplied by the stock 5.7 liter Vortec V8.

2. Approximately how much maximum peak power (expressed in Watts) does the Challenge Vehicle consume?

The Challenge Vehicle's electrical system will consume a maximum of 6000W electrical power. The power generated and used by the Vortec V8 is unknown.

3. What type and how much fuel will be carried by the Challenge Vehicle?

There will be three fuel tanks on board, all holding 87 octane unleaded gasoline. Two will provide fuel for the Challenge Vehicle engine, and one will provide fuel for the on-board generator. The two for the Challenge Vehicle engine are the stock Chevy 30-gallon gas tank and an auxiliary 15.5-gallon gas tank. The generator fuel tank will carry 16 gallons of gasoline. Therefore a total of 61.5 gallons of gasoline will be carried on board the Challenge Vehicle.

c. Processing

5. What kind of computing systems (hardware) does the Challenge Vehicle employ? Describe the number, type, and primary function of each.

The Challenge Vehicle will contain up to 9 regular desktop, IBM, Pentium 4, 3.0Ghz PC computers and an IBM laptop. The IBM PC computers will be devoted to the vehicle control system and vehicle state estimation, vehicle contingency management, stereo image processing (2), LADAR processing, road following, and global route planning. State estimation includes combined filtering from an inertial measurement unit (IMU), a magnetometer, and a DGPS unit to obtain position, heading and tilt angles. The IBM laptop is used as an interface to the IMU. All computers are networked via a 100 Mb/s Ethernet network.

6. Describe the methodology for the interpretation of sensor data, route planning, and vehicle control. How does the system classify objects? How are macro route planning and reactive obstacle avoidance accomplished? How are these functions translated into vehicle control?

We will use a combination of stereovision, LADAR and monocular vision to perform terrain estimation and evaluation. One short range and one long range pair of black and white stereovision cameras will produce point clouds at 30 Hz that we will process into local terrain maps at the same rate. This computation will be done with the Small Vision System purchased from Videre Systems. The local terrain maps will be UTM-oriented Cartesian grids that slide with the vehicle's motion, and which store terrain elevation and which can be filled with map information stored on the vehicle. Accurate map generation is ensured by closely synchronizing our terrain data with the sensed state of the vehicle at the time the data was taken.

One LADAR unit will be mounted on the roof of the vehicle angled downward, and another will be mounted on the front bumper pointing approximately straight. These units will scan in a plane and produce data that will also be entered into local maps as they sweep across the ground in front of the vehicle.

Another color camera will be mounted on the roof, time permitting, to provide image streams to custom road-following algorithms that our team has developed.

Macro route planning will be accomplished using a standard D* algorithm which evaluates over preprocessed maps that are stored on the vehicle's computers. This algorithm takes current position and a goal position and will generate target points that define an optimal path through the given map.

The path planning and reactive obstacle avoidance will be realized by synthesizing the output from each of the subsystems through a series of votes on a finite alphabet of motion primitives that are defined by the desired steering angle of the vehicle. These votes consist of a goodness of a particular primitive and the maximum safe velocity, according to each voter, that the vehicle can achieve along each primitive. The motion primitives are defined by the set of arcs traveled along evenly spaced potential steering angles, between full-left and full-right.

Given the votes generated by the stereovision code, LADAR, global path planning, and a dynamic feasibility evaluator, a supervisory agent called the arbiter will calculate the cost/benefit of traversing each arc, giving low scores to the ones with obstacles, rough terrain, and the like. The vehicle will avoid obstacles when necessary and stays on a predefined route otherwise.

The output of the arbiter at any given time will be the desired steering angle and speed of the vehicle, which will be sent to embedded systems code that perform tight control loops to track these desired values.

d. Internal Databases

1. What types of map data will be pre-stored on the vehicle for representing the terrain, the road network, and other mobility or sensing information? What is the anticipated source of this data?

We have obtained 1m resolution images of the entire possible race-course, minus censored data over military bases. The computer alone will not know what to do with the RGB maps, so we will “paint” terrain types onto the maps. Based on color pixel value the computer will be able to distinguish roads, railroad tracks, overpasses, water, mountains, buildings, dry lakes, vegetation areas, and off-road trails. Each terrain type has an associated cost of driving on it, and the D-Star algorithm will then determine the “least-expensive” path to take. Cost is roughly equivalent to the inverse of traversable-velocity, as roads, for example, would have a low cost and could be driven at high speeds. The course boundary is represented as an infinite cost, thus the route planner would never allow the vehicle to stray out of the course.

Our maps were downloaded from U.C. Davis and U.N. Reno and are part of the USGS data library. They are not new maps and therefore the system will need to adapt to new data collected during the race, including when there is no prior map data at all.

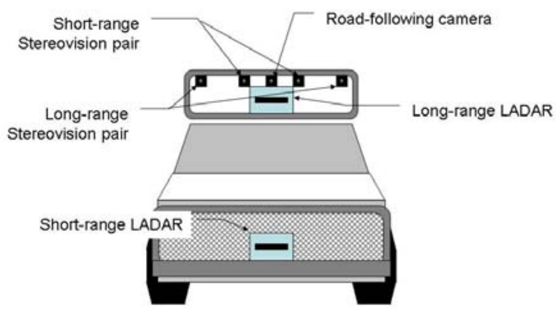
e. Environment Sensing

1. What sensors does the challenge vehicle use for sensing the environment, including the terrain, obstacles, roads, other vehicles, etc.? For each sensor, give its type, whether it is

active or passive, its sensing horizon, and its primary purpose.

Sensor	Type	Active or Passive	Sensing Horizon	Primary Purpose
Long-range forward-looking stereo camera pair	Dragonfly digital-output, black & white, 640 x 480 resolution cameras from Point Grey Research	Passive	94.3° horizontal field of view, 70.7° vertical field of view.	Used for detecting terrain, obstacles, roads, and other vehicles, at long range (more than 30 meters in front of vehicle) and at higher speeds.
Short-range forward-looking stereo camera pair	Dragonfly digital-output, black & white, 640 x 480 resolution cameras from Point Grey Research	Passive	44.6° horizontal field of view, 33.4° vertical field of view.	Used for detecting terrain, obstacles, roads, and other vehicles, at short range (within 30 meters in front of vehicle) and at low speeds.
Road following camera	Dragonfly digital-output, color, 640 x 480 resolution camera from Point Grey Research	Passive	94.3° horizontal field of view, 70.7° vertical field of view.	Road following
Bumper LADAR	SICK LMS-221-30206 single-axis	Active	100° horizontal plane	Obstacle avoidance & terrain classification, short range
Cab LADAR	SICK LMS-221-30206 single-axis	Active	100° horizontal plane	Obstacle avoidance & terrain classification, long range

2. How are the sensors located and controlled? Include any masts, arms, or tethers that extend from the vehicle.



Refer to the figure at left for sensor locations.

All of the sensors on board the vehicle are rigidly mounted to a steel frame.

The long-range LADAR sensor is mounted on top of the cab, pointing down. The short-range LADAR is mounted on the front bumper, also pointing down. The short-range stereovision pair, long-range stereovision pair, and road-following camera are mounted as shown in the figure (all pointing forward).

f. State Sensing

1. What sensors does the Challenge Vehicle use for sensing vehicle state?

For navigational and attitude state determination, the vehicle will use a combination of three different sensors. A Navcom SF-2050G DGPS system will provide latitude, longitude, and heading/velocity (when the vehicle is in motion). The heading reference generated by the DGPS system will be fed into a Northrop Grumman LN-200 Inertial Measurement Unit running in AHRS (Attitude, Heading, and Reference System) mode which then generates pitch and roll information. The LN-200 will be initialized using data from a PNI TCM2-50 3-axis magnetometer, which will provide heading, pitch, and roll data when the vehicle is stationary. Vehicle diagnostic state will be provided by the car's built-in On-Board Diagnostic system, which will provide, among other data, engine temperature, engine RPM, and present gear.

2. How does the vehicle monitor performance and use such data to inform decision making?

The vehicle senses its inertial state, engine state, and systems status to determine if there are failures in the components or if the vehicle is operating in unsafe conditions (e.g., excessive pitching moments). This information is used to modify the operations of the vehicle, via a vehicle contingency management module that can control the parameters in other software modules affecting the vehicle's operations.

g. Localization

1. How does the system determine its geolocation with respect to the Challenge Route?

   The vehicle determines its geolocation with respect to the grand challenge route through differential GPS.

2. If GPS is used, how does the system handle GPS outages?

   In cases of GPS outage, the vehicle will use the IMU and magnetometer to navigate. Zero-velocity updates will be used to reset the biases on the IMU, and the vehicle will integrate the delta-Vs and delta-thetas generated by the IMU to get position and attitude information. During the zero-velocity updates, the vehicle will also wait to see if GPS has been reacquired and use that information as an update to the inertial navigation.

3. How does the system process and respond to Challenge Route boundaries?

   The route boundaries are superimposed on our global maps, and are given infinite cost of traversibility. Therefore, the macro route-planner should never allow our challenge vehicle out of the course way.

h. Communications

4. Will any information (or any wireless signals) be broadcast from the Challenge Vehicle? This should include information sent to any autonomous refueling/servicing equipment.

   No signals will be sent during the race. We use 900MHz Freewave (www.freewave.com) ethernet radios for testing, but they will be removed for the race.

5. What wireless signals will the Challenge Vehicle receive?

   DGPS is the only signal our vehicle will receive. We have a Navcom DGPS unit which can receive GPS corrections from their Star-Fire satellite. This is a commercially available unit and signal.

i. Autonomous Servicing

There will be no autonomous servicing.

j. Non-autonomous control.

1. How will the vehicle be controlled before the start of the challenge and after its completion?

To control the vehicle, one must switch to human-control mode by flipping the "human-computer" switch (see figure at left). The driver will then have control of the stock accelerator pedal, stock brake pedal, transmission shift switch, and joystick (for steering). Actuators can be individually turned off using cutout switches located to the right of the steering wheel.

In brief, the method of operator interface includes:

- Brake pedal
- Accelerator pedal
- Steering wheel (joystick)
- Transmission shift switch
- Actuator cutout switches

2. If it is to be remotely controlled by a human, describe how these controls will be disabled during the competition.

The vehicle may be remotely controlled by a human via an Ethernet radio link, for testing purposes only. During the race, these radios will be removed from the vehicle, disabling this function.

2. System Performance

a. Previous Tests. What tests have already been conducted with the Challenge Vehicle or key components? What were the results?

Several system tests have been performed in the field.
1. <u>St. Luke's parking lot, Pasadena, CA, August 1, 2003:</u> The challenge vehicle was tested in a large empty parking lot to test the ability of the software to actuate the vehicle (braking, steering, throttle, etc.). The steer-by-wire capability was demonstrated, and some generator issues were identified and resolved.
2. <u>Santa Anita parking lot, Arcadia, CA, August 14, 2003:</u> Further testing of the actuation was accomplished. More generator issues were discovered and resolved. Computing integration issues (software bugs,

processor speeds) were discovered and resolved.
3. El Mirage Dry Lake Bed, near Adelanto, CA, August 20, 2003: GPS and magnetometer data was collected. Further testing of computer-controlled actuation.
4. Santa Anita parking lot, Arcadia, CA, September 12, 2003
5. Santa Anita parking lot, Arcadia, CA, September 17, 2003
6. Santa Anita parking lot, Arcadia, CA, November 8, 2003
7. Santa Anita parking lot, Arcadia, CA, November 15, 2003. Cruise control testing.
8. Santa Anita parking lot, Arcadia, CA, December 6, 2003
9. Santa Anita parking lot, Arcadia, CA, December 20-21, 2003
10. St. Luke's Hospital parking lot, Pasadena, CA, December 31, 2003
11. St. Luke's Hospital parking lot, Pasadena, CA, January 4, 2004
12. El Mirage Dry Lake bed, near Adelanto, CA, January 18, 2004
13. Caltech parking lot, January 25, 2004
14. Santa Anita parking lot, Arcadia, CA, February 16, 2004
15. Santa Anita parking lot, Arcadia, CA, February 22, 2004

Additional sub-system tests have been performed:
1. El Mirage Dry Lake Bed, near Adelanto, CA, May 11, 2003: This trip had several purposes.

a. Hard drive survivability: The purpose of this test was to determine what hard drive mounting methods, if any, would protect them from damage while driving off-road. Computers with spinning hard drives were installed in the back of the stock 1996 Chevy Tahoe. 6 hard drives were tested. Two were installed via a standard mount, two were encased in foam rubber, one was suspended by an 8-point spring mount, and one was mounted on rubber washers. The only disk to fail outright was the spring-mounted drive.
(For the race, only one of the 8 computers will need to use a mechanical hard drive at any time [for map data]. The other 7 computers will all hold the map data, but their disks will be spun down. The rated non-operating shock of these drives is 300G for a 2ms pulse, or 1.04Grms for vibration. This is much more than we expect to see. Thus, 8 independent failures would be required to disable the vehicle, an unlikely occurrence).

b. Maximum accelerations: A small 2-axis accelerometer was mounted in the vehicle to measure maximum accelerations inside the vehicle while traveling off-road. Maximum accelerations were measured under 2g.

c. OBD-II data collection: We used an off-the-shelf system (AutoTap) to read data from the On-Board Diagnostic (OBD) system that is part of all 1996 and later vehicles. We found the data from OBD-II to be less than reliable. Further testing is required to determine if any of the OBD-II data will be useful.

2. Infrared camera (El Mirage, August 9-10): We evaluated the

performance of the Indigo Omega (long-wave infrared) and the Indigo Merlin NIR (near-infrared) cameras. The images of the NIR camera were similar to those of a monochrome visible-light camera. The images of the long-wave camera, however, highlighted vegetation, negative obstacles, fence posts, and roads, even though the data was highly subject to cloudiness and time of day. The end result of the test was the decision to purchase a long-wave infrared camera.

3. <u>SICK LADAR:</u> Basic tests of our LADAR software have been performed. The LADAR was mounted on a donated shopping cart and driven through hallways to test the functioning of our software. In the future when the IMU (Inertial Measurement Unit) is running, testing of the software that builds a 3-D map from the LADAR data will be performed.

4. <u>Visible camera:</u> Tests of the physical ruggedness of the camera have been performed. Also, we have performed basic tests of the functionality of our cameras and the framegrabbers (images have been successfully captured).

5. <u>GPS</u>: We have tested the ability of various materials to block antenna reception. Flat sheets of aluminum and Lucite were unable to block the GPS, as multi-path reflections off of the ground still reached the antenna. Wrapping the antenna in aluminum foil cut off reception (we can selectively cut off satellites and simulate GPS outages). Also, we have checked the accuracy of the GPS coordinates of our maps.

6. <u>Computing results:</u> The IBM desktops can process 6.8 frames per second of stereo data at the required resolution. Our IPC software can exchange messages in 30us. The miscellaneous digital I/O on the "comm box" can switch in 1.3us.

b. Planned Tests. What tests will be conducted in the process of preparing for the Challenge?

With only a few days until QID, we have a few test days planned, at El Mirage and at the Santa Anita race track parking lot. They will be used to fine tune our stereovision and LADAR obstacle avoidance algorithms, in addition to our corridor following software.

3. Safety and Environmental Impact

a. What is the top speed of the vehicle?

For a variety of reasons, the top safe vehicle speed (whether controlled by a human via the joystick or by the on-board computers) is 40 mph.

b. What is the maximum range of the vehicle?

Greater than 250 miles, assuming (worst case) 5 miles/gallon, and 50 gallons of fuel.

c. Safety equipment

i. Fuel containment

The challenge vehicle will have both the stock 30-gallon gas tank and two auxiliary tanks. The fuel system is fully sealed and pressurized, tested to meet California standards for emissions and crash survivability. The vehicle's auxiliary fuel tank is mounted under the body, nested between the frame rails.

The generator fuel tank (a Jaz Products fuel cell, model 270-116-06, see image at left) is mounted inside the vehicle. It consists of a seamless cross-linked polyethylene inner shell, 20 gauge steel red powder coated outer container, Mil-Spec B-83054 aviation foam filled, a D-Ring bail handle cap assembly with check valve vent, and Mil-Spec anodized AN-8 pickup and tip valve vent.

ii. Fire suppression

Fire extinguishers will be installed at each corner of our vehicle. There will be no automatic fire suppression system.

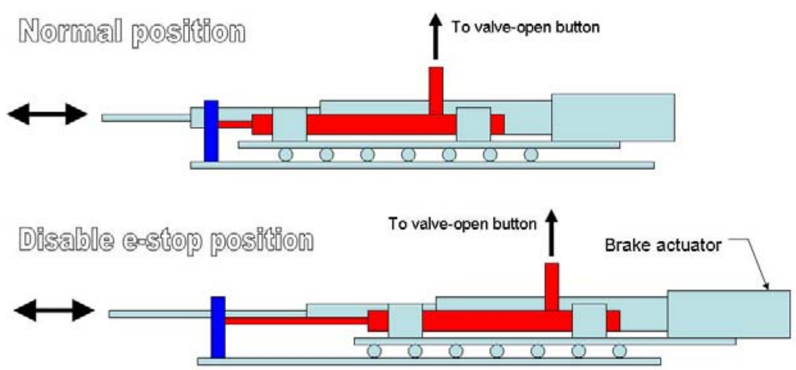
iii. Audio and visual warning devices

There will be a warning tone and light that both satisfy the requirements of the DARPA Grand Challenge rules.

d. E-Stops

i. How does the Challenge Vehicle execute emergency stop commands? Describe in detail the entire process from the time the on-board E-Stop receiver outputs a stop signal to the time the signal is cleared and the vehicle may proceed. Include descriptions of both the software controlled stop and the hard stop.

Disable E-stop: When a disable E-Stop signal is received (whether through the manual e-stop system or the wireless e-stop system), our E-Stop circuit will (1) cut power to the vehicle's ignition system and (2) cut power to two solenoids which results in full engagement of the brakes. See figure at left.



The brake actuator is a linear actuator that is attached to a cable. This cable is routed to the back of the vehicle's brake pedal. When the actuator retracts, the actuator pulls the cable and depresses the brake pedal.

The entire actuator is mounted on a sliding plate, as is a strong gas spring. During normal operation, the gas spring is fully retracted, and the actuator can control the brakes from full off to full on. During the disable e-stop, the gas spring is extended, which causes the brake actuator to pull hard on the cable attached to the back of the brake pedal, thereby depressing the brakes fully. The system has been designed such that the brakes will be depressed fully no matter what the position of the brake actuator.

The gas spring is extended by pressing a plunger that opens a valve on the gas spring. During the disable e-stop signal, the plunger is pressed by the mechanism described in the figure below:

The throttle and steering actuators will still have power, but the engine will be off, so no vehicle motion will be possible.

Pause E-stop: The software control e-stop (pause) is detected by the vehicle management computer and executes a sequence of functions that bring the vehicle to a stop. This is accomplished by signaling the planning software that a pause signal has been received, at the same time as commanding the vehicle velocity to zero within the cruise control loop.

When the software control e-stop is released (resume), the planning software is notified and the vehicle controller begins to receive commands from the planning computer.

ii. Describe the manual E-Stop switch(es). Provide details demonstrating that this device will prevent unexpected movement of the vehicle once engaged.

The manual E-Stop switches will be four red mushroom switches located around the vehicle. These mushroom switches are connected to our E-Stop circuit. When activated, a hard E-Stop will be executed, and the vehicle will decelerate and remain motionless (see 3.d.i. above).

iii. Describe in detail the procedure for placing the vehicle in "neutral", how the "neutral" function operates, and any additional requirements for safely manually moving the vehicle. Is the vehicle towable by a conventional automobile tow truck?

Procedure to place the vehicle in neutral: (1) Ensure the emergency brake is engaged (push the foot pedal to the left of the brake pedal). (2) locate the human interface box (see picture at left). (3) Switch to "human" control, then (4) rotate the transmission knob to "neutral". This cuts power to the transmission actuator, allowing it to move in and out with little force applied. (5) Pull the cable attached to the transmission actuator all of the way out – this is the vehicle's "park" position, which has been converted a second neutral position (by removing the parking pawl). (6) Disengage emergency brake by pulling black knob to the left of the steering motor.

Vehicle towing: The vehicle may be towed using a conventional tow truck, at any safe speed (there is no limitation on wheel speed – we are no longer using foam-filled tires).

e. Radiators

i. Itemize all devices on the Challenge Vehicle that actively radiate EM energy, and state their operating frequencies and power output. (E.g., lasers, radar apertures, etc.)

Device: SICK LMS-221 single-axis LADAR
Operating frequency: Infrared
Power output: Class 1 Laser.

ii. Itemize all devices on the Challenge Vehicle that may be considered a hazard to eye or ear safety, and their OSHA classification level.

> There are no devices on our challenge vehicle that are considered a hazard to eye or ear safety (except possibly the DARPA-required audible warning device).

iii. Describe any safety measures and/or procedures related to all radiators.

> Our SICK LADAR uses a class 1 laser, which is neither hazardous to eyes nor capable of acting as an ignition source. Accordingly, it is unnecessary to take safety precautions related to our only radiator.

f. Environmental Impact

i. Describe any Challenge Vehicle properties that may conceivably cause environmental damage, including damage to roadways and off-road surfaces.

> The vehicle will produce approximately the same level of emissions as an unmodified pickup and is well within California standards for gaseous and particulate emissions. The vehicle will achieve approximately 8-10 miles per gallon, assuming standard conditions. The generator will consume an additional 1 gallon per hour. The vehicle is equipped with standard radial tires so damage to road surfaces will be minimal.

ii. What are the maximum physical dimensions (length, width, and height) and weight of the vehicle?

> The maximum width of our challenge vehicle is 84”, the height is just under 96” and the length is just under 200”. The weight of the vehicle is ~ 6000 lbs.

iii. (Dave) What is the area of the vehicle footprint? What is the maximum ground pressure?

> Each tire footprint is ~ 90 square inches, so assuming a 30% tread void given our tires, the maximum ground pressure is approximately 24 psi.